Separating ν's and $\bar{\nu}$'s with a non-magnetized detector

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Project X Physics Study

Outline

1. MiniBooNE and wrong-sign contamination in the Booster Neutrino Beam (BNB)
2. Three measurements of ν_μ flux in BNB $\bar{\nu}_\mu$ beam
3. Technique utility out to PX era

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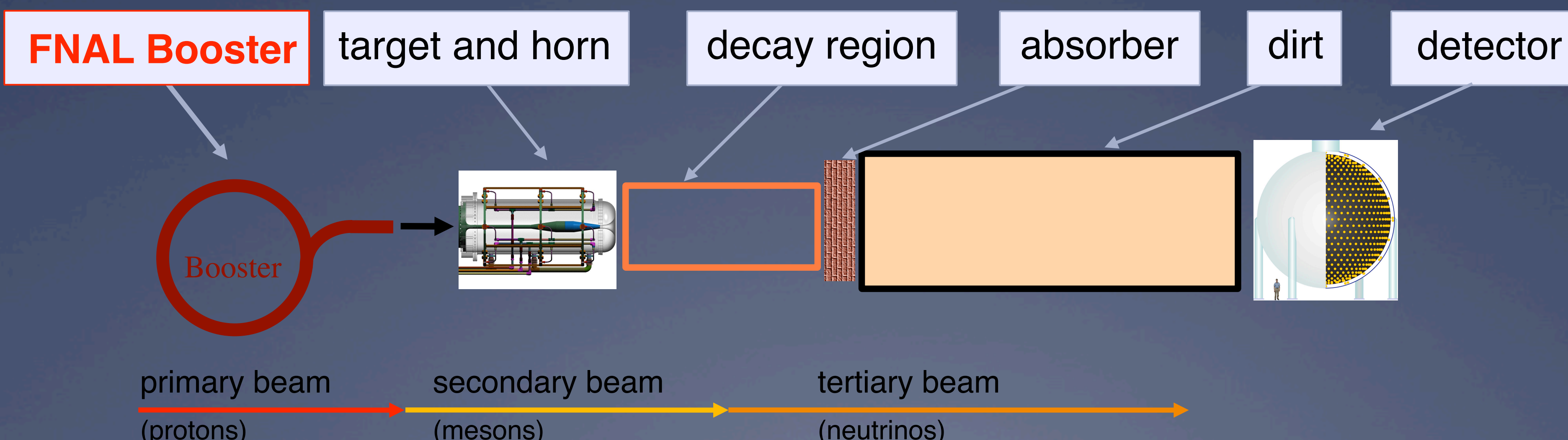
Booster Neutrino Beam

8.9 GeV/c momentum protons extracted from Booster, steered toward a Beryllium target in bunches of 5×10^{12} at a maximum rate of 5 Hz



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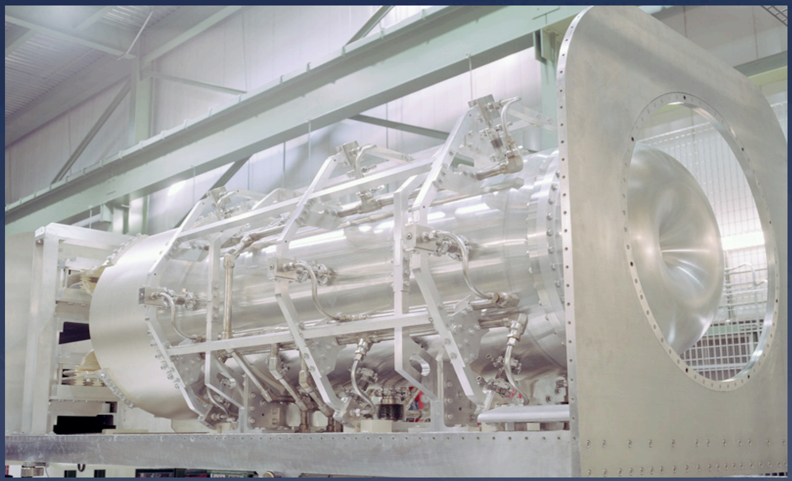
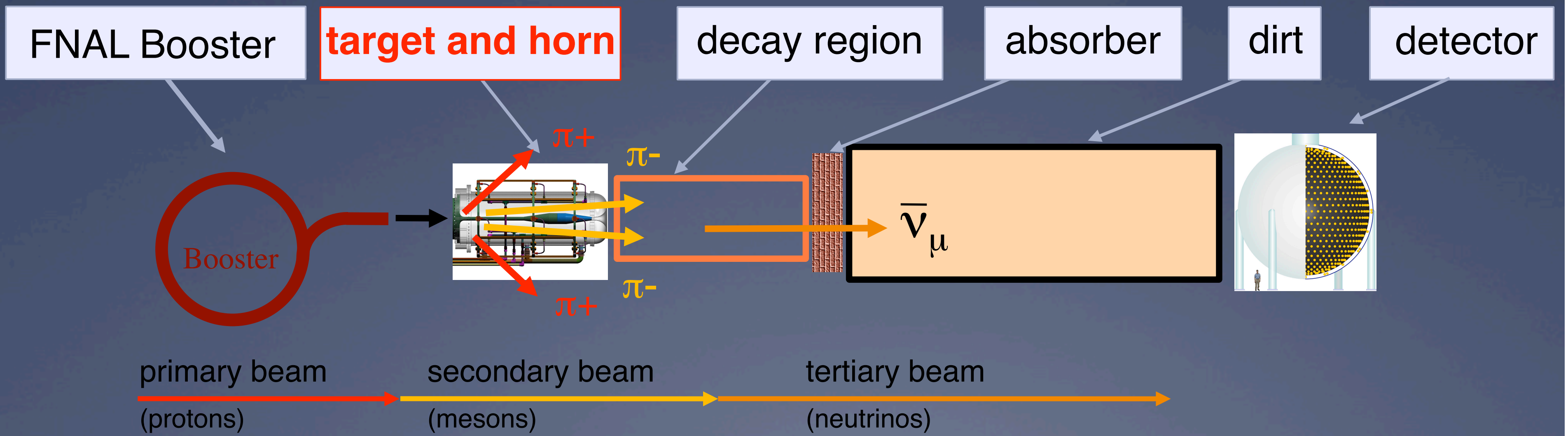


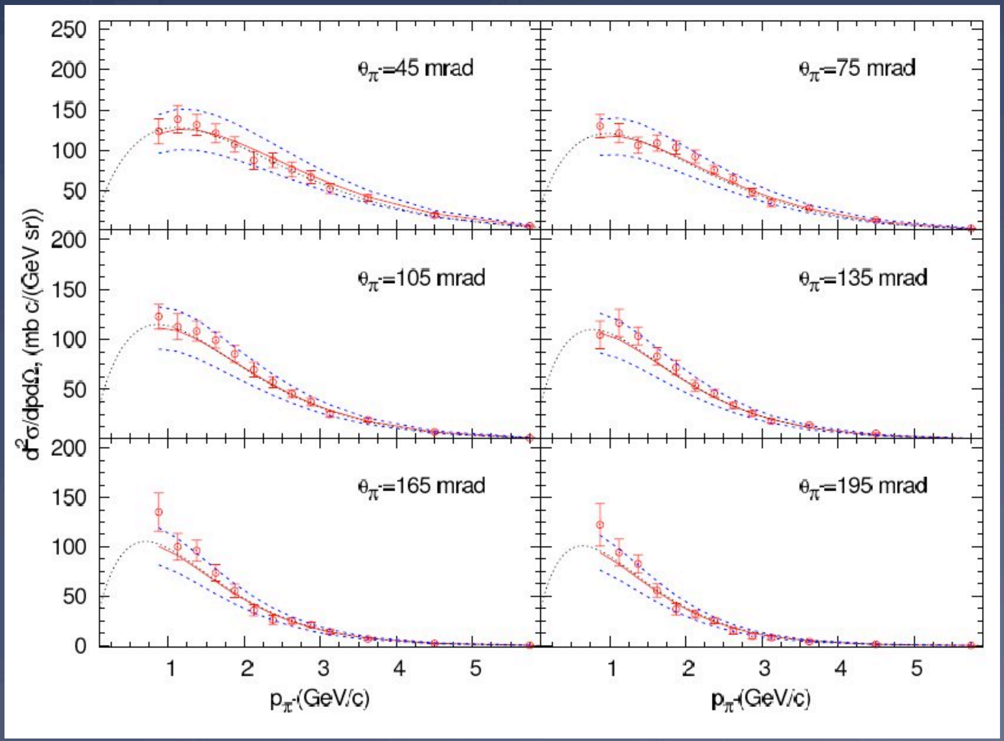
Magnetic horn with reversible polarity focuses either neutrino or anti-neutrino parent mesons

("neutrino" vs "anti-neutrino" mode)

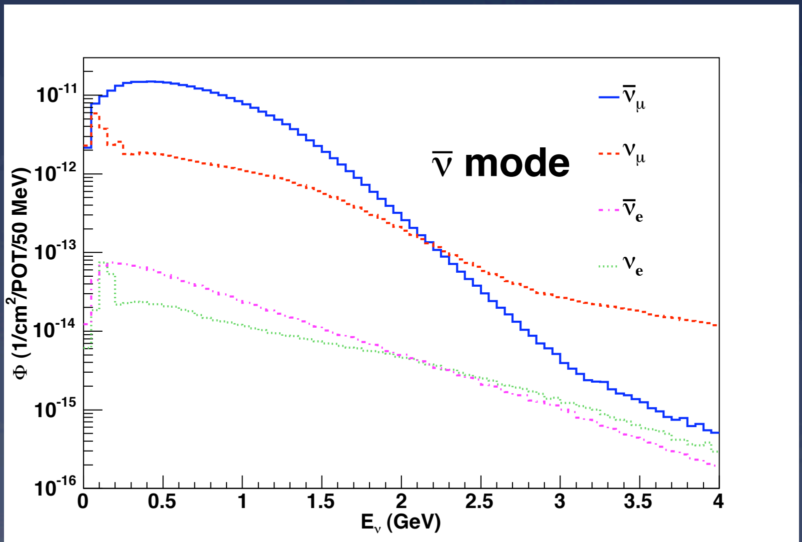


MiniBooNE Flux

- Flux prediction for "right signs" based exclusively on external data - no *in situ* tuning



HARP collaboration,
Eur. Phys. J. C52 29 (2007)

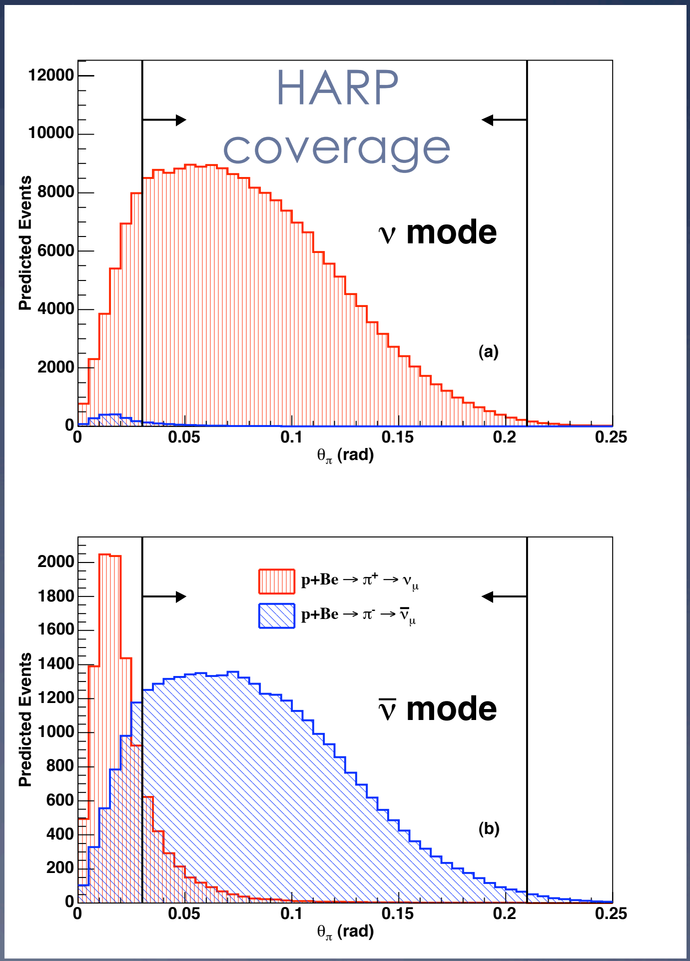


MiniBooNE collaboration,
Phys. Rev. D79, 072002 (2009)

- Dedicated pion production data taken by HARP experiment to predict neutrino flux at MiniBooNE
- A spline fit to these data brings flux uncertainty to ~9%

MiniBooNE Flux

* ~9% errors only true for pions produced in HARP-covered phase space
* Due to large proton background, pion production below 30 mrad not reported
* While not a serious issue for neutrino mode (top plot), severe complication for anti-neutrino mode (bottom)



Why so different?

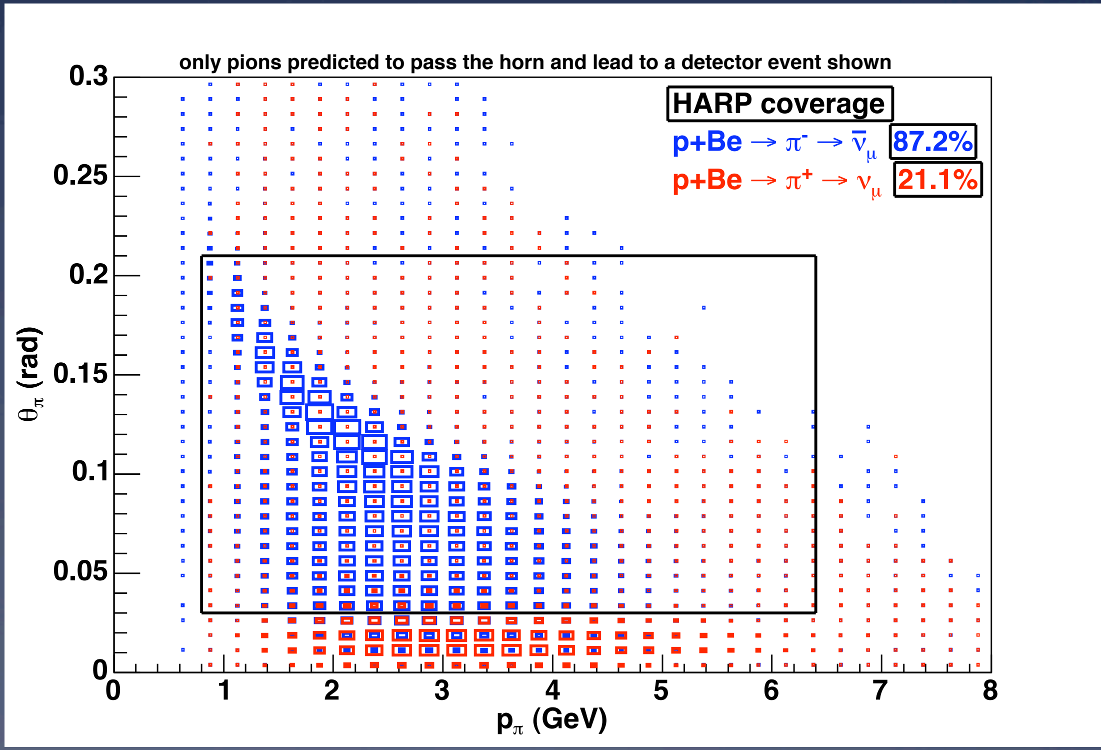
- Cross section: at MiniBooNE energies (E_ν~1 GeV), neutrino cross section ~ 3x higher than anti-neutrino

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 |V_{ud}|^2}{8\pi E_\nu^2}\left[A\left(Q^2\right) \boxed{\pm} B\left(Q^2\right)\left(\frac{s-u}{M^2}\right) + C\left(Q^2\right)\left(\frac{s-u}{M^2}\right)^2\right]$$

- Flux: leading particle effect creates ~ 2x as many π+ as π-

How wrong signs contribute to flux

* Wrong-sign pions escape magnetic deflection and contribute to the anti-neutrino beam via low angle production



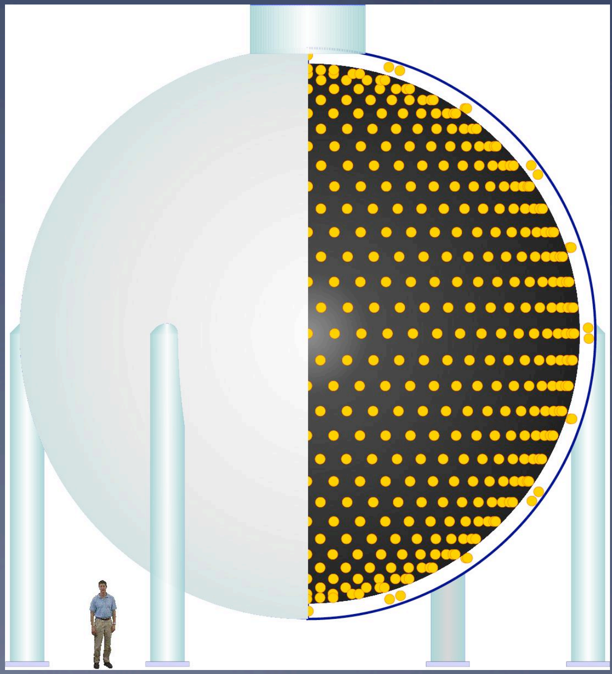
* In anti-neutrino mode low-angle production is a *crucial* flux region and we do not have a reliable prediction

This motivates a dedicated study of ν_μ content of the beam

MiniBooNE detector

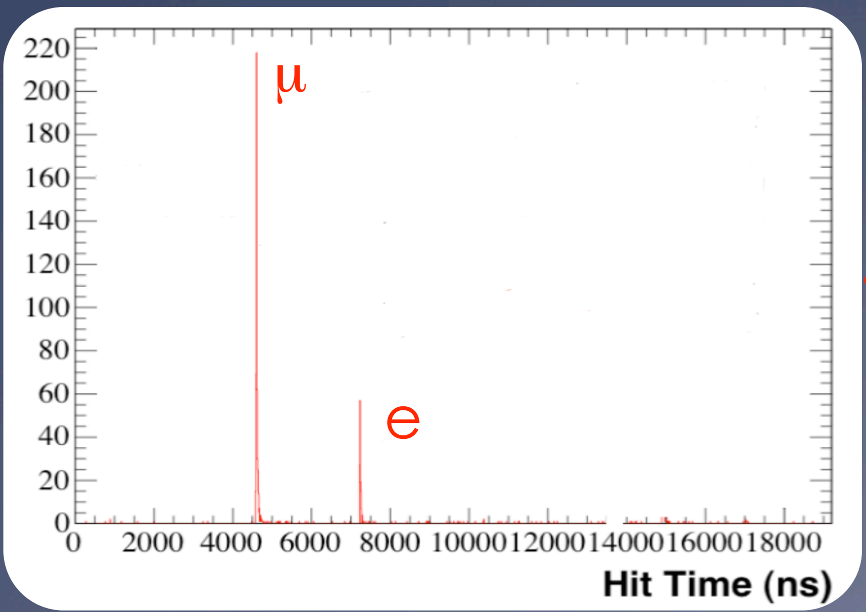
- 6.1m radius sphere houses 800 tons of pure mineral oil.
- 1520 Photo Multiplier Tubes uniformly dispersed in 2 regions of tank (240 veto, 1280 inner tank)
- No B-field!
- in situ calibration systems:
  - Laser system calibrates PMT response, tracks oil quality
  - Cosmic ray muon system calibrates detector response to muons and associated decay michel electrons

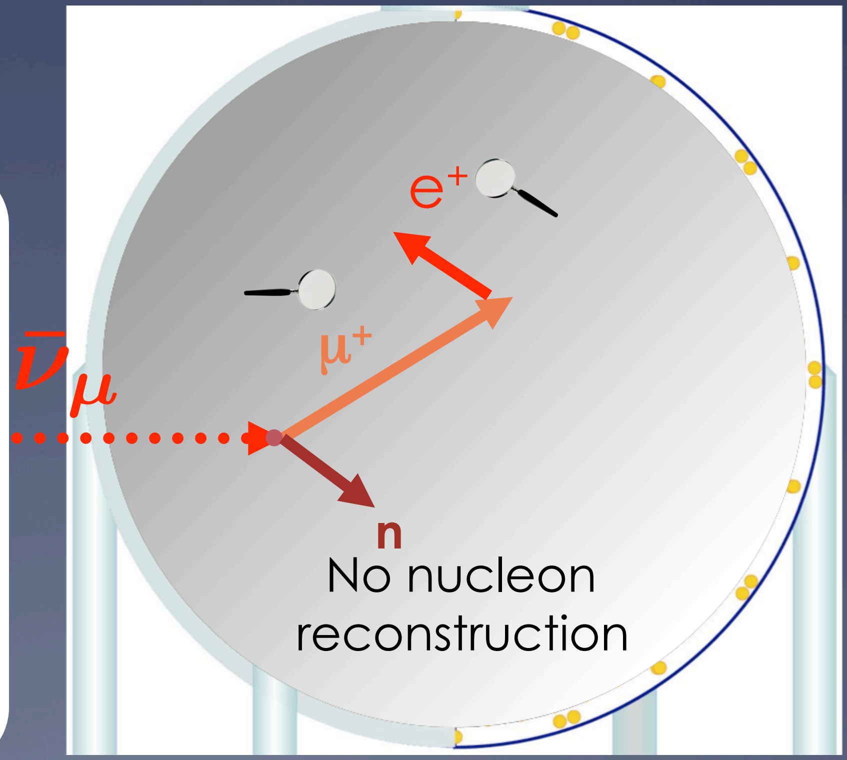
Nucl. Instr. Meth. A599, 28 (2009)



CCQE Events in MiniBooNE

CCQE is the most prevalent interaction at MiniBooNE's energy range, accounting for ~40% of all events.





1. Booster Neutrino Beam (BNB)
2. Three measurements of ν_μ flux in BNB $\bar{\nu}_\mu$ beam
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Wrong-sign measurements

* Three independent and complementary measurements of the wrong-sign background:

    1. Fitting the angular distribution of the CCQE sample for the neutrino and anti-neutrino content
    2. Comparing predicted to observed event rates in the $CC\pi^+$ sample
    3. Measuring how often muon decay electrons are produced (exploits μ^- nuclear capture)

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First measurement of the ν_μ content of a $\bar{\nu}_\mu$ beam using a non-magnetized detector.
Phys. Rev. D81: 072005 (2011)

Wrong-sign measurements

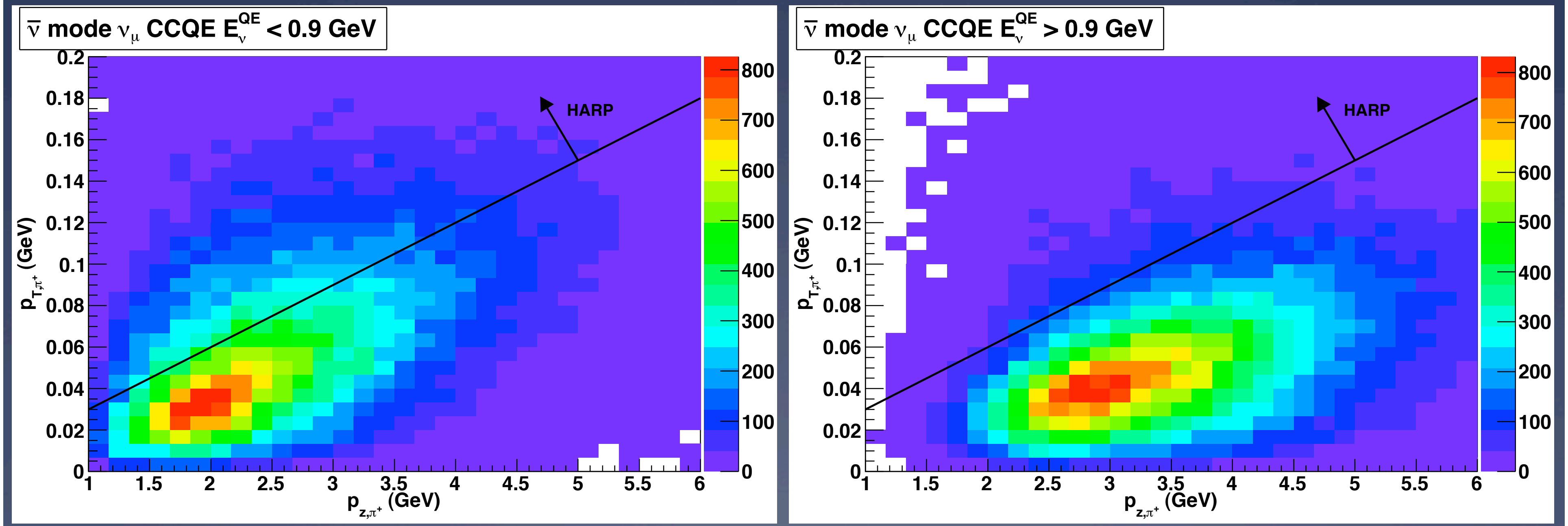
- General strategy: isolate samples sensitive to the ν_μ beam content, apply the measured cross sections from neutrino mode (CCQE, CCπ^+)
  - *Crucial* application of BooNE-measured ν_μ σ's

$$\frac{\mathrm{Rate}^{\mathrm{data}}}{\mathrm{Rate}^{\mathrm{sim}}} = \frac{\Phi^{\mathrm{true}} \times \sigma}{\Phi^{\mathrm{sim}} \times \sigma} = \frac{\Phi^{\mathrm{true}}}{\Phi^{\mathrm{sim}}}$$

- The level of data-simulation agreement then reflects the accuracy of the ν_μ flux prediction

Wrong-sign measurements

- Important to bin in E_ν as finely as possible to check ν_μ flux spectrum



- Different energies have different relative HARP coverage too - might expect flux accuracy to be $f(E_\nu)$

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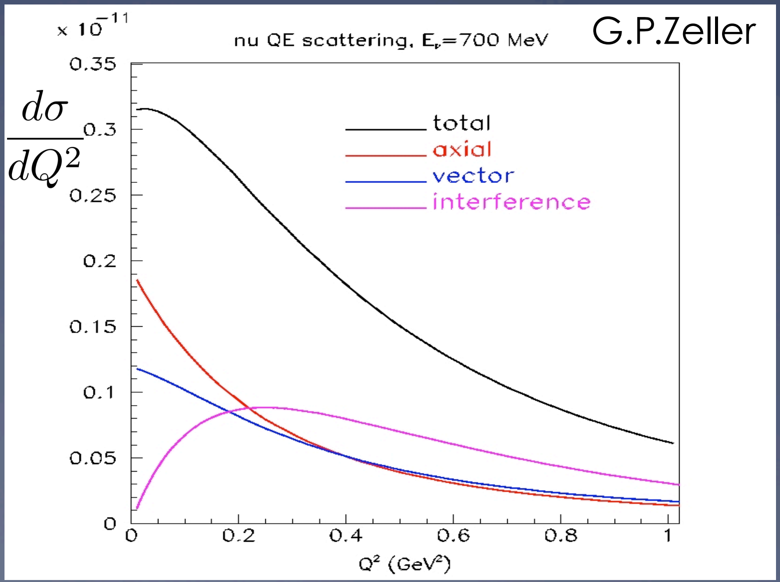
Fitting the outgoing muon angular distribution

- Neutrino vs anti-neutrino CCQE cross sections differ exclusively by an interference term that changes sign between the two

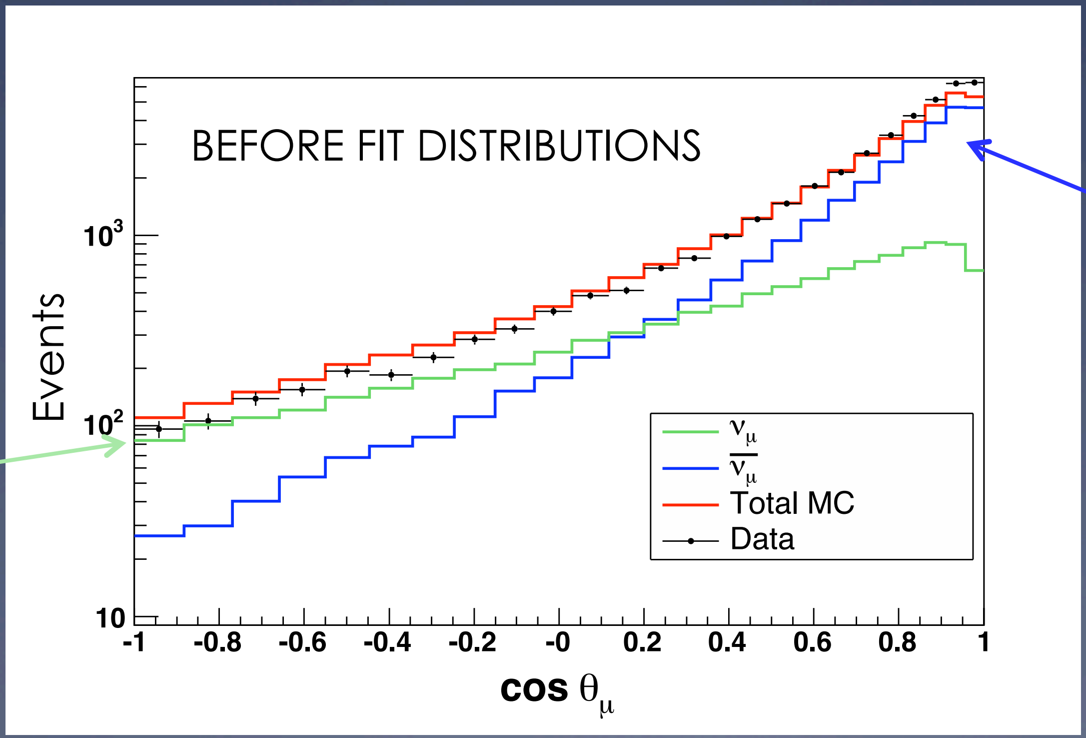
$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 |V_{ud}|^2}{8\pi E_\nu^2}\left[A\left(Q^2\right) \boxed{\pm} B\left(Q^2\right)\left(\frac{s-u}{M^2}\right) + C\left(Q^2\right)\left(\frac{s-u}{M^2}\right)^2\right]$$

- The divergence is more pronounced at higher Q^2, which is strongly correlated with backward scattering muons



Fitting the outgoing muon angular distribution

- We form a linear combination of the neutrino and anti-neutrino content to compare with CCQE data:

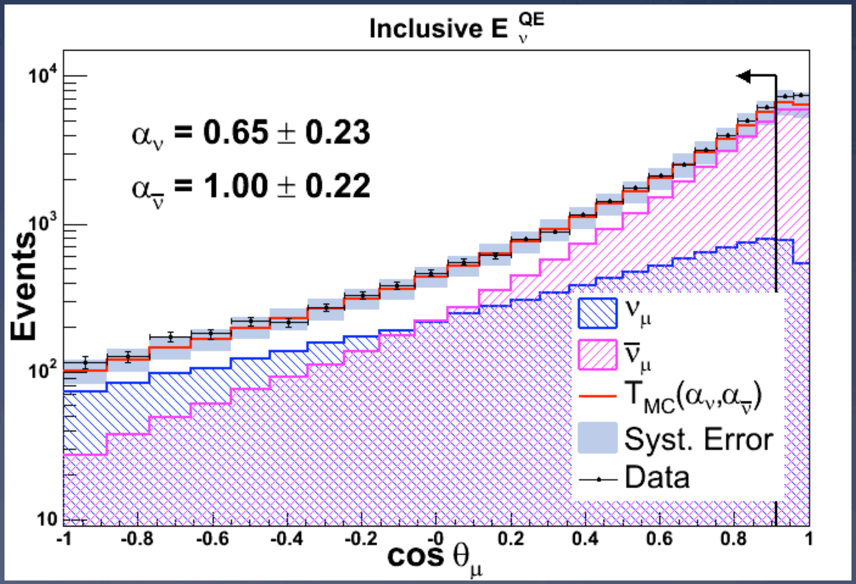


Scale the $\overline{\nu}_\mu$ template by "$\alpha_{\overline{\nu}}$"

Scale the ν_μ template by "α_ν"

Fitting the outgoing muon angular distribution

- Results indicate the ν_μ flux is over-predicted by ~30%
- Fit also performed in bins of reconstructed energy; consistent results indicate flux spectrum shape is well modeled

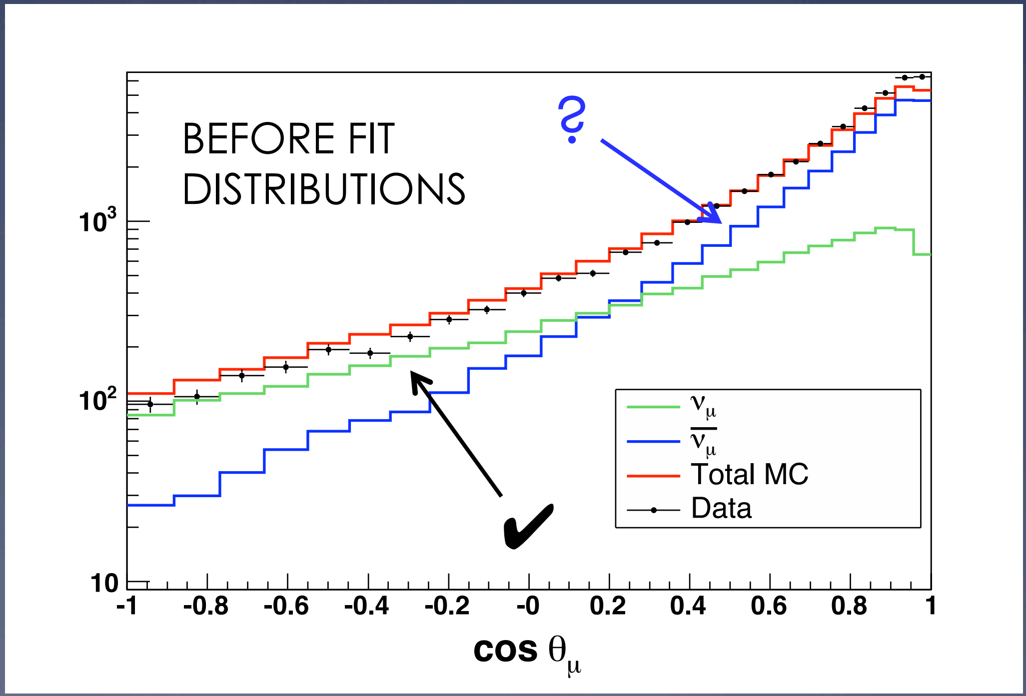


$\mathbf{E}_{\bar{\nu}}^{\mathbf{QE}}(\mathrm{MeV})$	α_ν	$\alpha_{\bar{\nu}}$
< 600	0.65 ± 0.22	0.98 ± 0.18
600 - 900	0.61 ± 0.20	1.05 ± 0.19
> 900	0.64 ± 0.20	1.18 ± 0.21
Inclusive	0.65 ± 0.23	1.00 ± 0.22

Model dependence

* Though the ν_μ CCQE scattering template is known (from our measurement), the result is correlated to the (unknown) anti-ν_μ distribution and therefore biased

* In Project X era, σ's should be much better known and this technique could be very powerful



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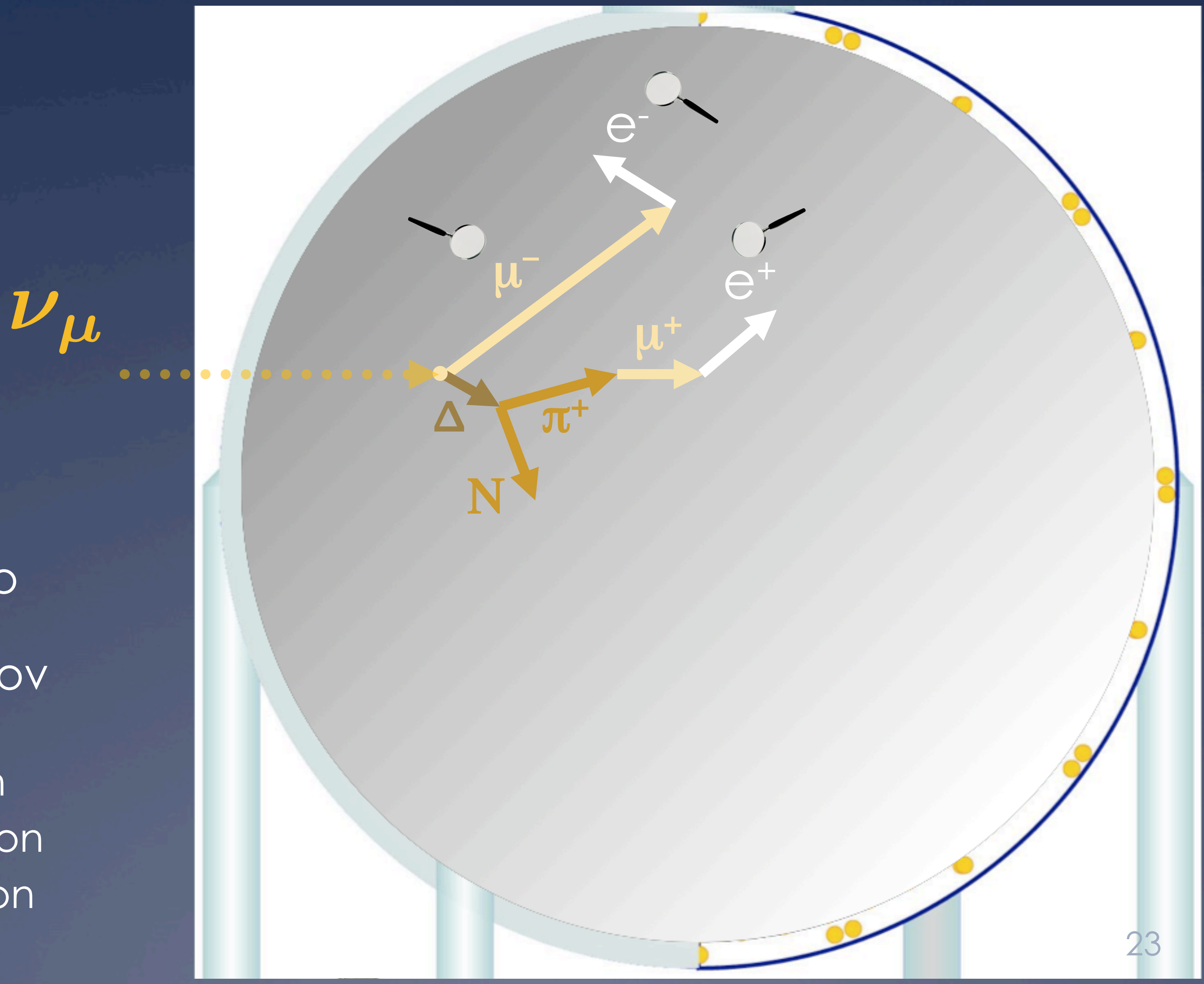
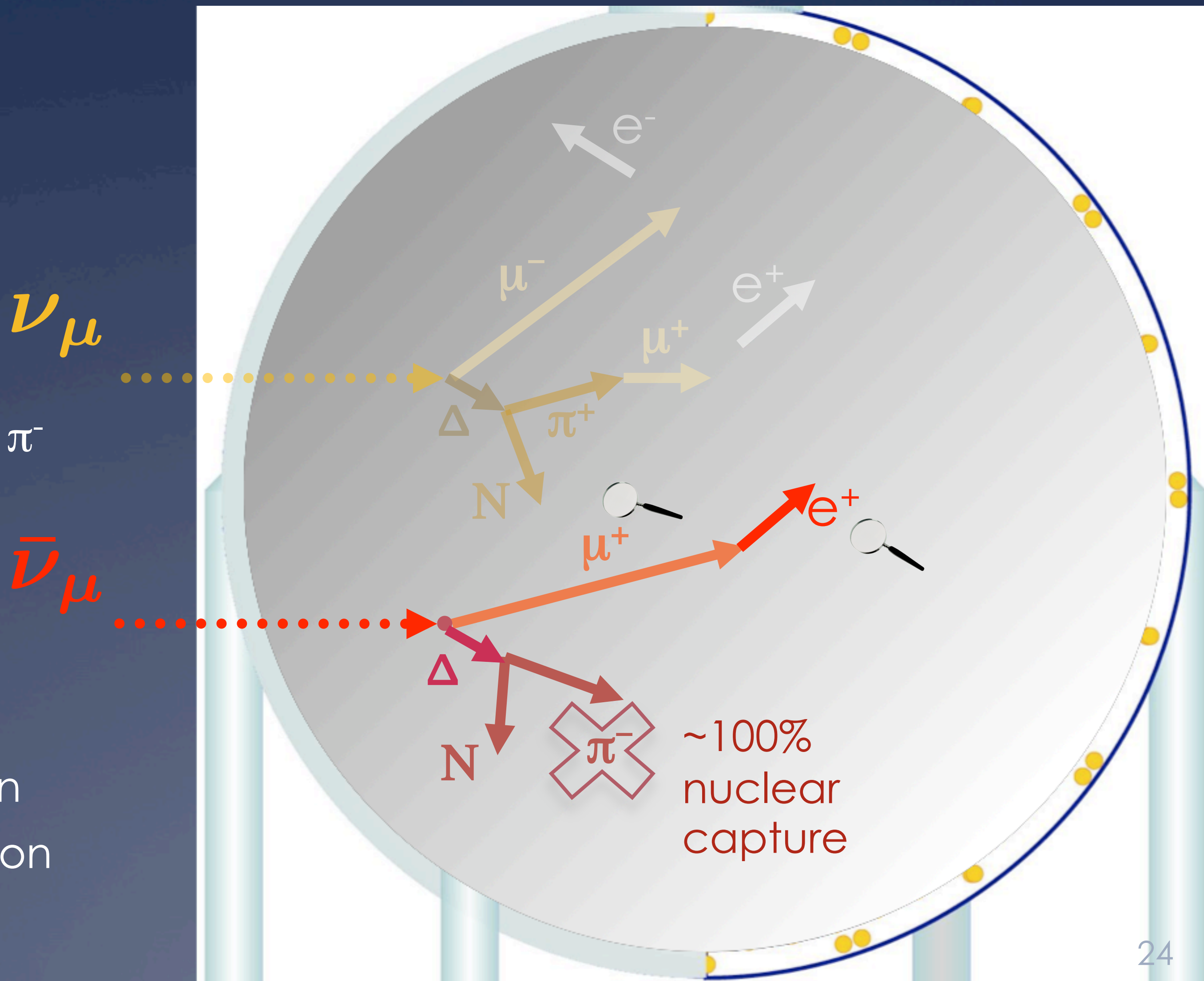
CCπ^+ sample formation



* The neutrino induced resonance channel leads to three leptons above Cherenkov threshold
    1. Primary muon
    2. Decay electron
    3. Decay positron

CCπ^+ sample formation

- Due to nuclear π^- capture, the corresponding anti-neutrino interaction has only two:
  1. Primary muon
  2. Decay positron



$CC\pi^+$ ν_μ flux measurement

- With the simple requirement of two decay electrons subsequent to the primary muon, we isolate a sample that is ~80% neutrino-induced.

- Data/simulation ratios in bins of reconstructed energy indicate the neutrino flux is over-predicted in normalization, while the spectrum shape looks fine

E_ν^Δ (MeV)	ν_μ Φ scale
600 - 700	0.65 ± 0.10
700 - 800	0.79 ± 0.10
800 - 900	0.81 ± 0.10
900 - 1000	0.88 ± 0.11
1000 - 1200	0.74 ± 0.10
1200 - 2400	0.73 ± 0.15
Inclusive	0.76 ± 0.11

$CC\pi+$ σ measurement:
Phys. Rev. D83, 052007 (2011)

Wrong-sign measurements

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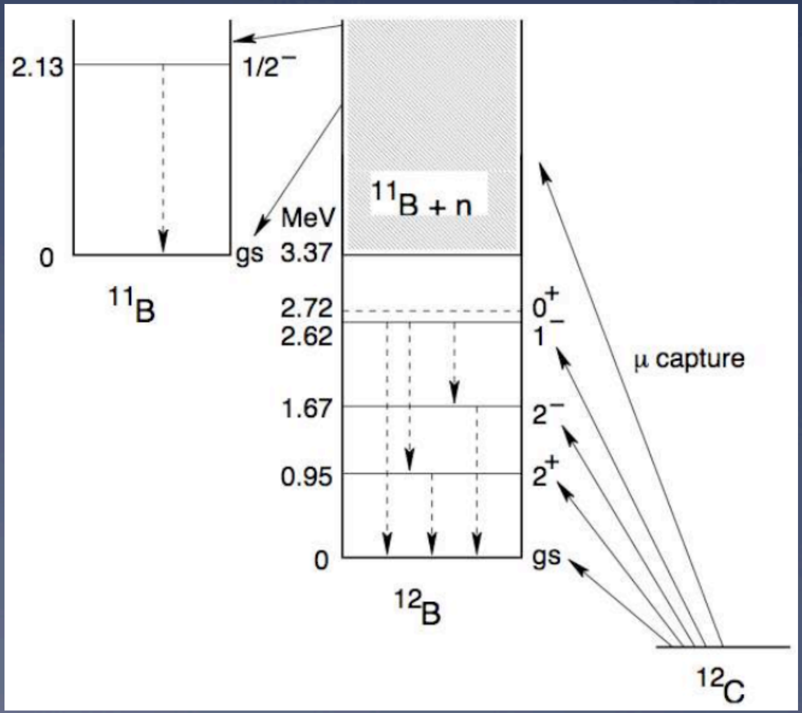
μ^- capture measurement

- CC events typically observe both μ+e - two reasons why we may not observe the decay electron:
  1. Michel electron detection efficiency
  2. μ^- nuclear capture (ν_μ CC events only)
- We isolate a > 90% CC sample for both μ-only and μ+e samples

μ^- capture measurement

- ~8% of stopped μ^- captures on ^{12}C, but some nuclear de-excitation products (γ's,n's) can fake Michel electron
  - "regain" Michel-like event following ~6% of μ^- captures



- ν-mode data has very little wrong-sign contribution, so we use the observed μ+e to μ-only migration rate to calibrate nuclear de-excitation and Michel detection models
  - < 5% calibration

μ^- capture measurement

* By requiring $(\mu\text{-only}/\mu\text{+e})^{\text{data}} = (\mu\text{-only}/\mu\text{+e})^{\text{MC}}$ and normalization to agree in the μ+e sample we can calculate a ν_μ flux scale α_ν and a rate scale $\alpha_{\bar{\nu}}$

$$\frac{\mu}{\mu + e}^{\text{data}} = \left(\frac{\alpha_\nu \, \nu^\mu + \alpha_{\bar{\nu}} \, \bar{\nu}^\mu}{\alpha_\nu \, \nu^{\mu+e} + \alpha_{\bar{\nu}} \, \bar{\nu}^{\mu+e}} \right)^{\text{MC}}$$

Predicted neutrino content in the μ+e sample, for example

μ^- capture measurement

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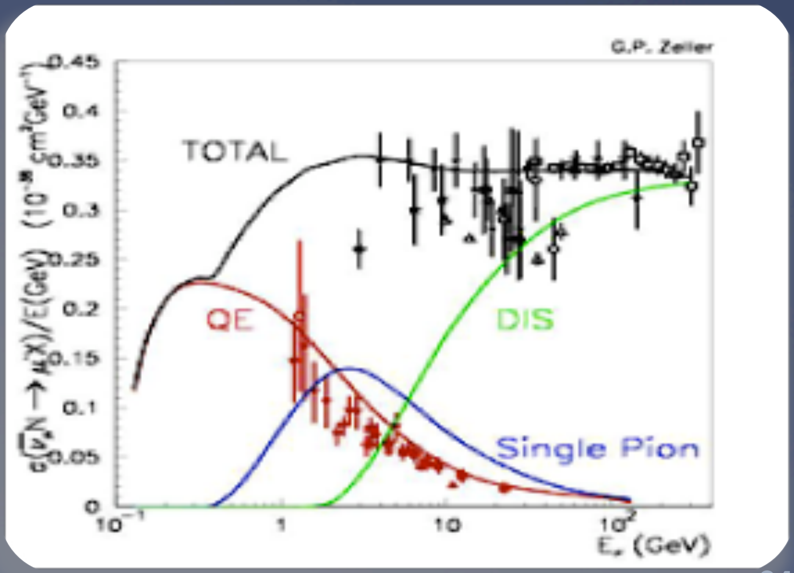
Results:

PRELIMINARY

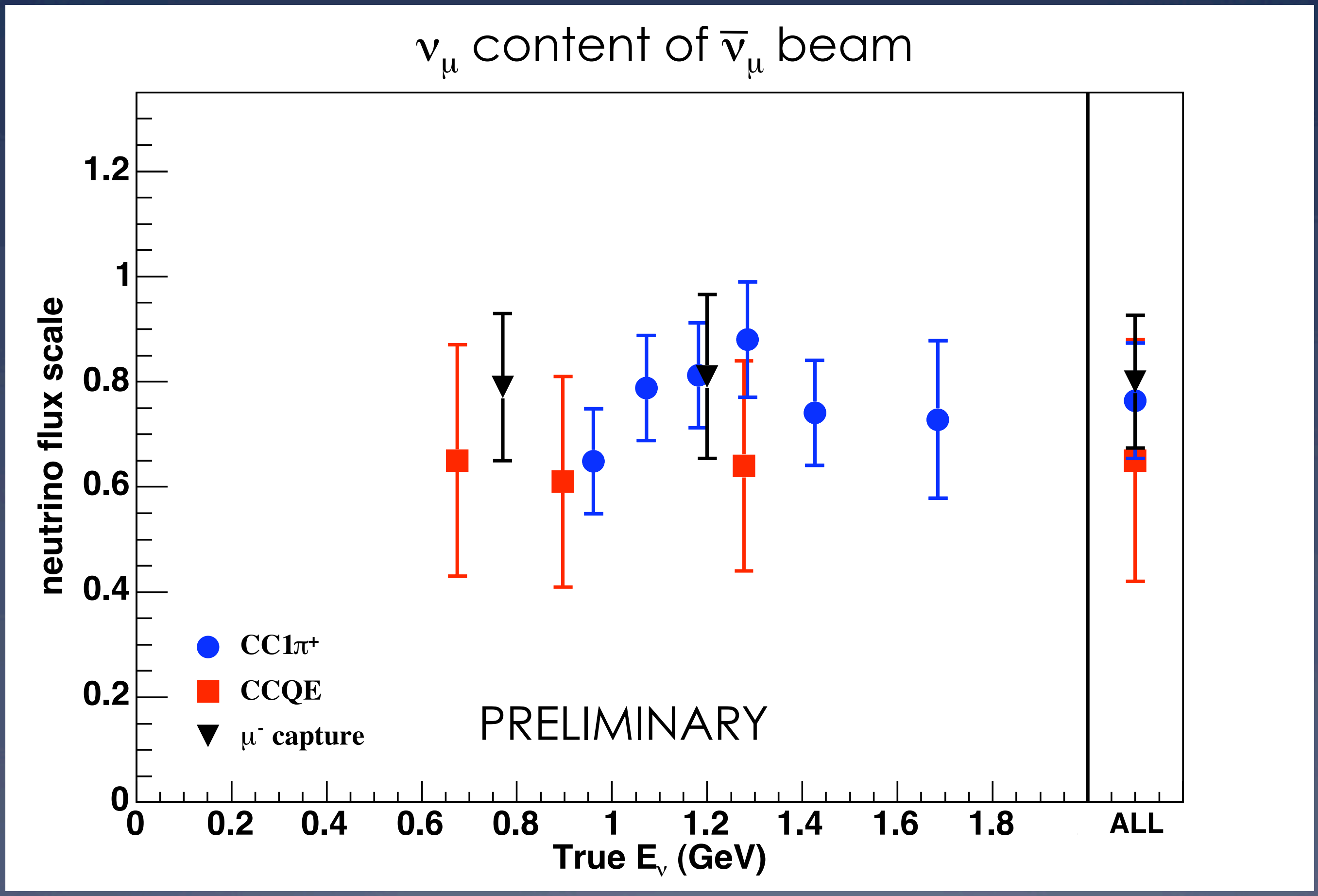
Parameter	E_ν^{QE} (GeV) < 0.9	E_ν^{QE} (GeV) > 0.9	All
α_ν	0.79 ± 0.14	0.81 ± 0.16	0.80 ± 0.13
$\alpha_{\bar{\nu}}$	1.14 ± 0.22	1.14 ± 0.22	1.14 ± 0.22

Model dependence?

- The μ+e sample is ~60% anti-ν_μ, how much model dependence enters from anti-ν_μ σ's?
- Flux measurement negligibly sensitive to anti-ν_μ σ: model would have to be wrong by > 50% to see an impact on extracted ν_μ Φ (it's not)
- This is accomplished with 8% μ^- capture for carbon. Can do much better with argon at ~75%!



Neutrino flux measurement summary

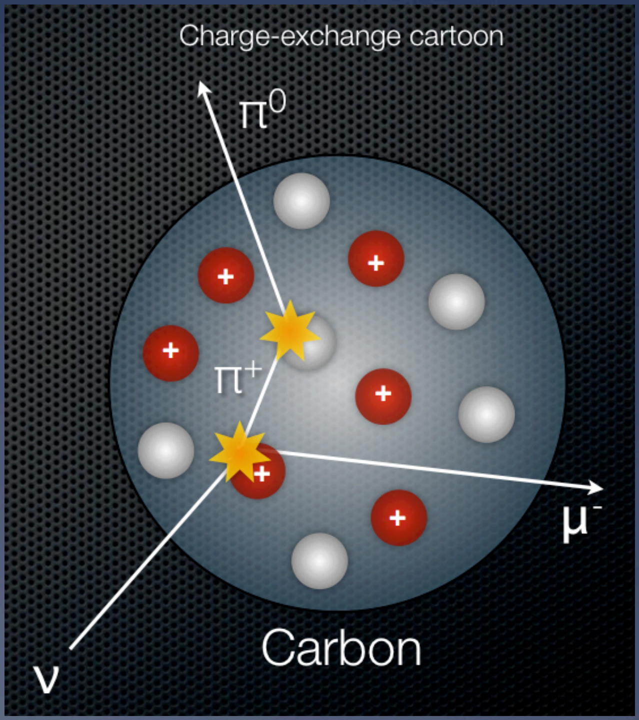


- Discrepancy with prediction appears to be in normalization only - flux shape is well modeled. 13% error on final measurement

Using your own σ measurements

* Most detector errors cancel by correcting anti-ν mode MC for σ's observed in the ν exposure

* Similar to two-detector osc experiments, but instead of one beam + 2 detectors, we use two beams + one detector



Φ measurement insensitive to FSI!

Strategy revisited

* General strategy: isolate samples sensitive to the ν_μ beam content, apply the measured cross sections from neutrino mode (CCQE, CCπ^+)
  * *Crucial* application of BooNE-measured ν_μ σ's

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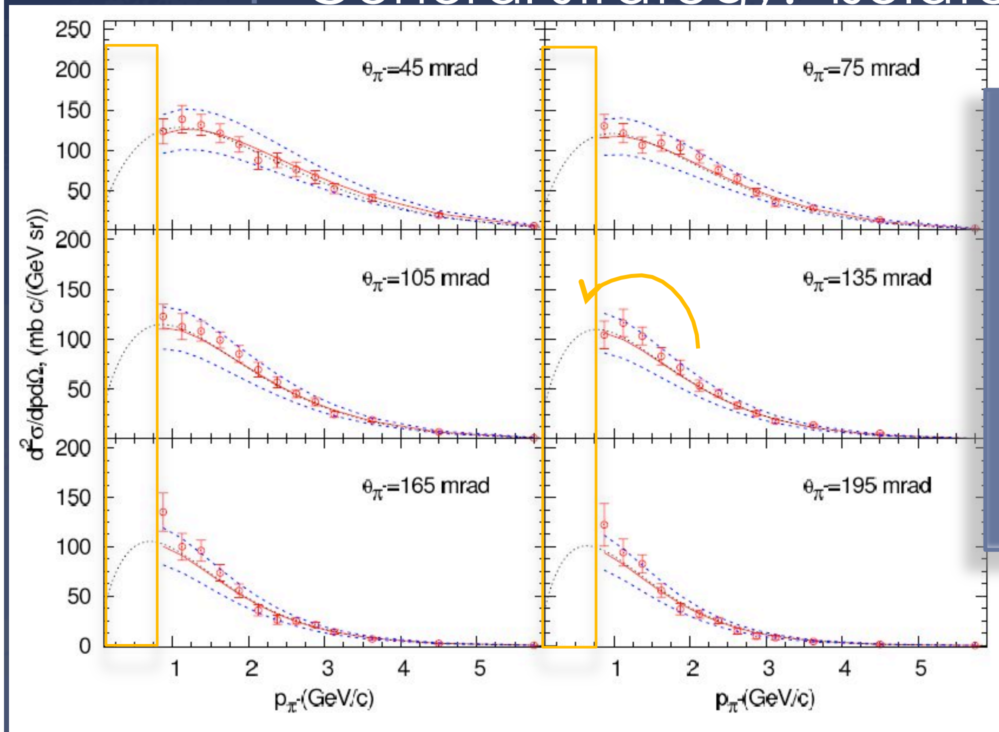
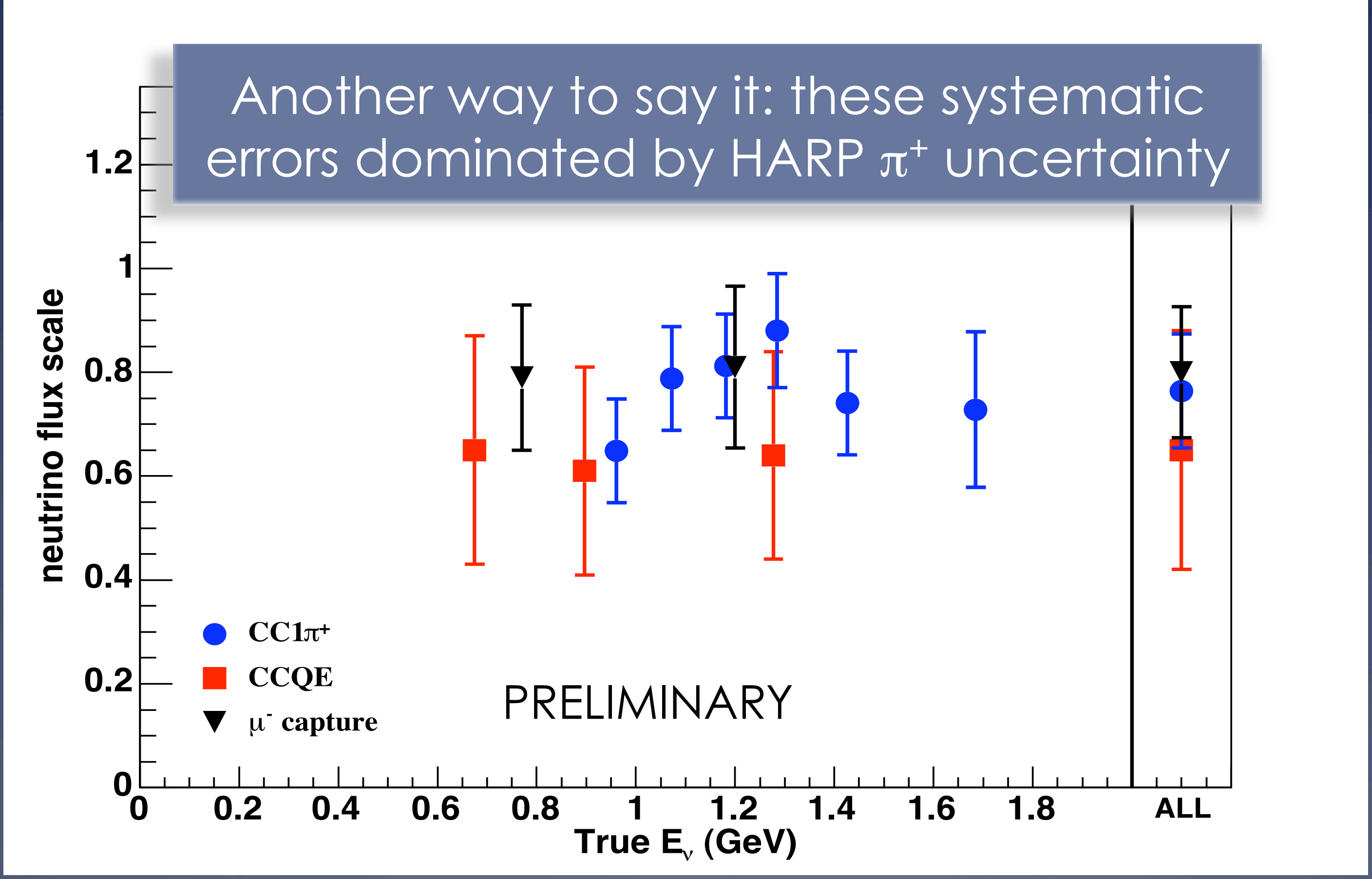


Takes hadro-production data, uses it to place similar constraints on the flux region *not measured*

on agreement then
the ν_μ flux prediction

Strategy revisited

Another way to say it: these systematic errors dominated by HARP π^+ uncertainty



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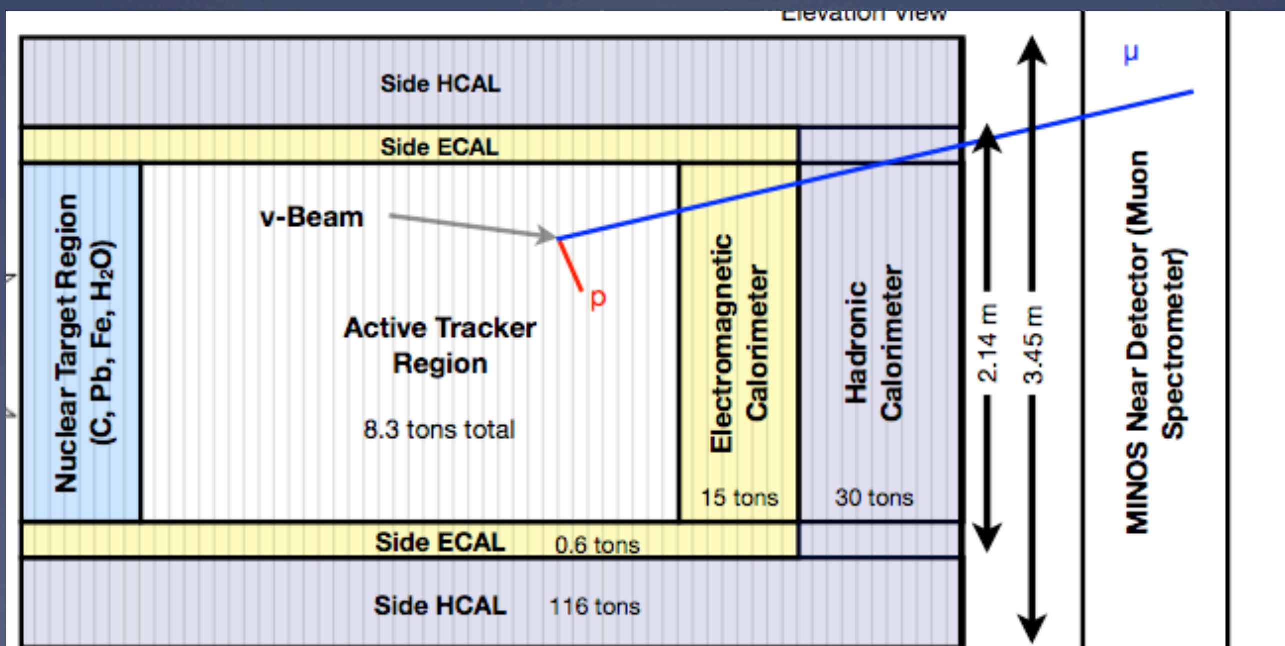
Current and future expts

- Nova (neither detector magnetized)
- Minerva: can get powerful statistical increases, more kinematic coverage (via μ angle) if use μ's stopped in main detector



Current and future expts

- LBNE: at user's meeting we heard Steering Group "strongly favors" new beamline with single LAr-TPC detector at Homestake.
- If no B-field, μ^- capture technique could be very powerful in wrong-sign discrimination w/o ND
  - 8% μ^- capture in carbon gives enough statistical power to separate ν from anti-ν in energy bins, argon has ~75% Phys Rev C 35 ,2212 (1987)
  - almost event-by-event discrimination without B-field!
  - ICARUS has demonstrated Michels can be reconstructed well in argon Eur Phys J C33, 233 (2004)

Other handles

* Fit μ lifetime to combination ν + anti-ν templates
  * different way of using μ capture
* Nuclear recoil - for "classical" CCQE, expect outgoing p for ν_μ, outgoing n for anti-ν_μ events. A few issues:
  * meson exchange currents predict combo. of p+n ejection in both cases (unclear energy dependence, nucleon kinematics)
  * final state interactions
  * proton detection modeling
  * we ought to be much better informed come the PX era

Conclusions

- Though MiniBooNE is unmagnetized, model-independent statistical techniques measure the ν_μ content in the $\bar{\nu}_\mu$ beam to ~13% uncertainty
- This is the first demonstration of a set of techniques that could well be used in the near future for CP-violation, mass hierarchy and σ measurements